³He ENHANCEMENTS IN LARGE SOLAR ENERGETIC PARTICLE EVENTS

G. M. MASON,[1,2] J. E. MAZUR,[3] AND J. R. DWYER[1]

ABSTRACT

We have measured the ³He abundance from ∼0.5 to 2 MeV nucleon⁻¹ in 12 large solar energetic particle (SEP) events during the period 1997 November–1999 June. In five of the events, the ³He time-intensity profile is similar to the ⁴He time-intensity profile, indicating a common acceleration and transport origin for the two species. The average ³He/⁴He ratio during these events is $(1.9 \pm 0.2) \times 10^{-3}$, a factor of ∼5 enhancement over the solar wind value. During this same survey period, we have also measured the low-energy ion intensities during quieter periods in between the large-particle events. We find ³He and Fe remnants from impulsive events present on a majority of the days, implying that they fill a substantial volume (>50%) of the in-ecliptic interplanetary medium during our survey. We suggest that these suprathermal ions may therefore be a source population that is available for further acceleration by interplanetary shocks that accompany large SEP events, thereby leading to the ³He enhancements in a significant fraction of large SEP events. This impulsive SEP event material might also account for recent observations of large solar particle events with energetic particle ionization states that have a wide range of ionization states that encompass values expected for both gradual and impulsive solar SEP events.

Subject headings: acceleration of particles — cosmic rays — interplanetary medium — solar wind — Sun: flares

1. INTRODUCTION

Solar energetic particles (SEPs) carry important clues to mechanisms of particle energization at astrophysical sites, as well as properties of the acceleration sites themselves. Although their properties vary from event to event, two basic classes have been identified as so-called "gradual" and "impulsive" events (see, e.g., review by Reames 1995). Gradual solar particle events are associated with coronal and interplanetary shocks, high particle intensities, and energetic particle abundances similar to the corona. Impulsive events are associated with short timescales, small particle intensities, and energetic particle abundances with modest (factor ∼10–20) enhancements of Ne-Fe and extremely large (sometimes exceeding 10^4) enhancements of ³He. In addition, particle ionization states in impulsive events are significantly higher than for gradual events, indicating a source region with temperatures of 10^7 K rather than $(2–4) \times 10^6$ K for gradual events.

Isolated reports of large (presumably gradual) SEP events with significant ³He, thus of "mixed" character, have been reported but had appeared to be rare (Dietrich 1973; Van Hollebeke, McDonald, & Meyer 1990; Chen, Guzik, & Wefel 1995). However, new instruments on the *Advanced Composition Explorer* (*ACE*) spacecraft have identified both ³He enhancements and high ionization states in several large-particle events, thus blurring the hitherto reasonably clean distinction between impulsive and gradual events (Cohen et al. 1999; Mason et al. 1999; Mazur et al. 1999; Möbius et al. 1999b). In this Letter, we examine this issue further by surveying ³He abundances in all large solar particle events observed over a 22 month period of rising solar activity.

2. OBSERVATIONS

2.1. ³He *Enhancements in Large Solar Particle Events*

The observations presented here were carried out with the Ultra–Low-Energy Isotope Spectrometer (ULEIS) on the *ACE*

spacecraft, launched in 1997 August. ULEIS is a time-of-flight mass spectrometer with resolution greatly exceeding previous instruments in its energy range of ∼0.02–10 MeV nucleon⁻¹ (Mason et al. 1998). An important feature of the ULEIS particle identification is the ability to make two time-of-flight measurements for each ion, thereby allowing identification and removal of background events. An example of the excellent mass resolution and low background of ULEIS is shown in Figure 1, which displays mass histograms for the large solar particle events in this study. Figure 1*a* is for a selection of events in which ³He was clearly present, while Figure 1*b* shows the sum of data for events in which only an upper limit on ³He could be determined.

In order to focus on large, shock-associated events during the survey period, we restricted the choice to those appearing in the NOAA Space Environment Center (SEC) preliminary solar proton event table, which consists of events whose intensity above 10 MeV exceeds 10 s⁻¹ cm⁻² sr⁻¹. This list has 15 events from the *ACE* launch through 1999 mid-June; ULEIS observed 12 of these events, which are listed in Table 1. In the table, the second through fourth columns are the associated solar flare data from the NOAA/SEC table; the fifth column is the time interval used here, the sixth column is the 0.5–2.0 MeV nucleon⁻¹ ³He/⁴He ratio, and the seventh column is the energetic particle ³He/⁴He enhancement compared to the slow solar wind. The time intervals listed in the fifth column were based on the particle intensities near 0.2 MeV nucleon⁻¹ and are therefore different from the durations seen at higher energies. Upper limits in Table 1 are all 1 σ. In the table, the accuracy of the ³He/⁴He measurement can be seen to vary from event to event; this is due to a number of variables that differ from one event to another, such as background level, event duration, and instrument operating state.

The paradigm for "gradual" solar particle events has the expectation that the energetic particles are accelerated out of the solar wind or its suprathermal tail, and therefore the predicted ³He/⁴He ratio is expected to be close to that of the solar wind, namely ∼4×10^{-4} (e.g., Reames 1995). Table 1 shows that in contrast, only four of the 12 events have upper limits of ³He/⁴He consistent with this value; the other eight events

[1] Department of Physics, University of Maryland, College Park, MD 20742; glenn.mason@umail.umd.edu.
[2] Institute for Physical Science and Technology, University of Maryland.
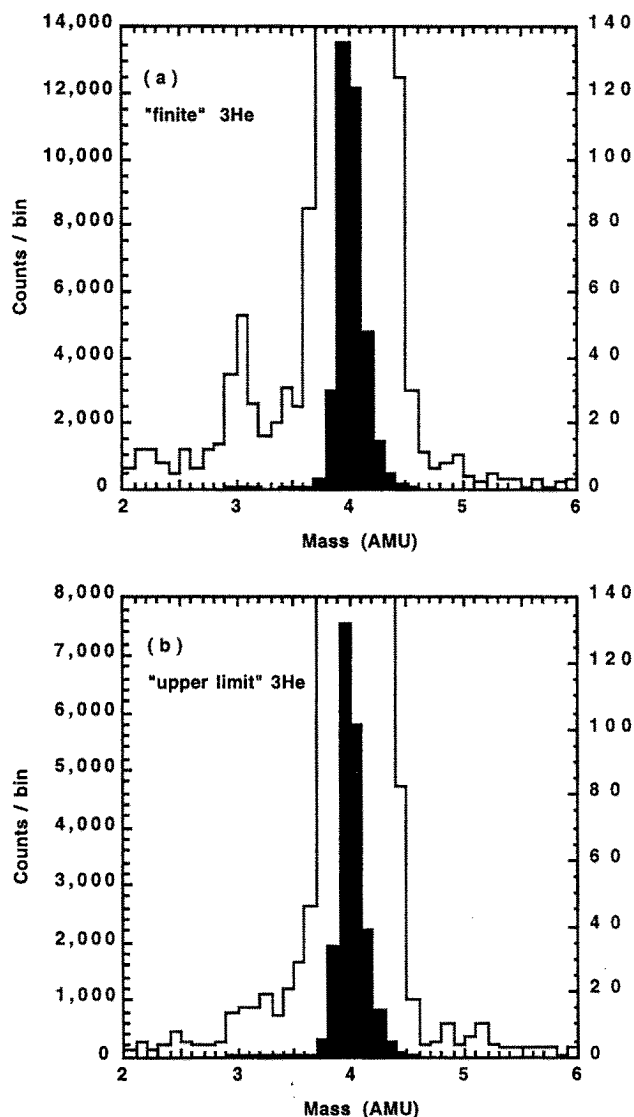[3] Aerospace Corporation, Los Angeles, CA 90009.

FIG. 1.—The 0.5–2.0 MeV nucleon^{-1} mass histograms for (*a*) events 1, 2, 5, 10, and 12 and (*b*) events 3, 6, 7, and 9. Left-hand scales apply to the shaded peak; right-hand scales are expanded to show the ³He region and background.

have finite ³He/⁴He ratios that are substantially larger. Figure 2 shows the time-intensity profiles for ³He and ⁴He during the 1999 day 155 event; the close similarity of the ³He and ⁴He profiles indicate that the ³He in this event is indeed associated with the larger event. This similarity of time-intensity profiles for ³He and ⁴He was also seen for events 2, 5, 10, and, with greater uncertainty, event 1.

Of the three remaining events in Table 1 showing finite ³He (i.e., numbers 4, 8, and 11), events 4 and 11 had low-energy time-intensity profiles that were irregular and not clearly related to the high-energy proton increase that caused the events to be included in the SEC table. In the case of event 8, the ³He injection occurred during a subperiod of the overall event, as has been reported occasionally in other cases (Mason et al. 1989), and therefore in this case the finite ³He appears to be due to an impulsive event that took place while the multiday gradual event was underway. In order to concentrate on reasonably simple events, we set aside events 4, 8, and 11.

Mass histograms of the events with "finite" ³He (1, 2, 5, 10,

and 12) are shown in Figure 1*a*, while the mass histograms for the events with upper limits (3, 6, 7, and 9) are shown in Figure 1*b*. For the finite event set, a linear background interpolation under the peak yields ³He/⁴He = (1.9 ± 0.2) × 10^{-3}, and for the upper limit events the fit yields ³He/⁴He < 1.0 × 10^{-3}. For the finite periods, the ³He/⁴He ratio exhibits no significant energy dependence over the range 0.2–1.5 MeV nucleon^{-1}. Compared with the slow solar wind ³He/⁴He ratio of (4.08 ± 0.25) × 10^{-4} (Gloeckler et al. 1999), the finite period has an enhancement of a factor of ∼5, while for the "upper limit" periods, the enhancement is less than 2.5.

2.2. *Impulsive Events during the Survey Period*

During our survey period, solar activity as measured by sunspot number and flare occurrence rose considerably. As an example of impulsive event activity in the range below 1 MeV nucleon^{-1} covered by ULEIS, Figure 3 is a spectrogram of ion arrival times for a series of impulsive events observed in 1998 August. During such periods in between large SEP events, ULEIS has observed dozens of small impulsive events rich in ³He and/or Fe. The clustering of these events in series, such as shown in Figure 3, has been reported previously. However, a new feature revealed in the low-energy range covered by ULEIS can also be seen in this figure, namely that the duration of the events is quite long at very low energies. For example, note that at the upper energy range of the plot (∼1 MeV nucleon^{-1}), the events present are of short duration. At the lower energy range of the plot (∼0.04 MeV nucleon^{-1}), single events continue for the better portion of a day. Taking the whole range ∼0.04–1 MeV nucleon^{-1}, it can be seen that impulsive SEP particles are present roughly 50% of the time during this 5 day period. During this interval, the Sun rotated ∼65°; therefore, a substantial volume of the interplanetary space near 1 AU contained impulsive SEP particles at this time.

In order to survey the incidence of impulsive events for the entire survey period, we used the Fe intensity at 200 keV nucleon^{-1}, since Fe enhancements often accompany ³He events and are a more reliable ion to identify because there is no nearby species with much higher abundance. Table 2 lists five logarithmically spaced intensity ranges for 200 keV nucleon^{-1} Fe, labeled A–E in order of increasing intensity. Levels A and B are "quiet," level C is typical of periods such as that shown in Figure 3, while levels D and E are typical of large-particle events. Notice that more than 55% of the time falls in periods with flux levels B and C; thus, there are low, nonzero intensity increases of Fe more than half the time during the survey. ³He is also present during these same periods as shown in Figure 4, which displays the 0.2–2 MeV nucleon^{-1} mass histogram for time intervals corresponding to intensity level B. Depending on the assumptions regarding the shape of the background under the ³He peak, the deduced ratio ³He/⁴He is 1%–2%. Even for the level A interval, there are finite amounts of ³He present, with ³He/⁴He ∼1%, well above the instrumental background limit and similar to that found in the level B periods. Thus, ³He is present in the interplanetary medium considerably more than 50% of the time during the survey period.

Inspection of daily plots verifies that the ³He shown in Figure 4 arrives on numerous days and is not the result of a handful of larger events; this inspection also makes clear that the presence of ³He increases during the survey period, as might be expected given the increase in the number of solar active regions. Obviously, the fraction of days when ³He is present would thus be expected to change during the course of a solar

TABLE 1
LARGE SOLAR PARTICLE EVENT TIME PERIODS

	ASSOCIATED SOLAR FLARE[a]			ENERGETIC PARTICLE EVENT		
EVENT NUMBER	Maximum (year, day of year/UT)	Importance	Location	Time (year, day of year)	^{3}He/^{4}He ($\times 10^{-4}$)	^{3}He Enhancement
1	1997, 308/05:58	X2/2B	S14, W33	1997, 309.0–310.0	19 ± 5	4.7 ± 1.3
2	1997, 310/11:55	X9/2B	S18, W63	1997, 312.25–314.0	20 ± 5	4.9 ± 1.3
3	1998, 110/10:21	M1/EPL[b]	S43, W90	1998, 110.5–111.625[c]	<9	<2.2
4	1998, 122/13:42	X1/3B	S15, W15	1998, 122.5–124.0	130 ± 20	32 ± 5
5	1998, 126/08:09	X2/1N	S11, W65	1998, 126.6–128.3	35 ± 7	8.6 ± 1.8
6	1998, 236/22:12	X1/3B	N30, E07	1998, 237.2–242[d]	<14	<3.4
7	...[e]	...	...	1998, 310–312.0	<6	<1.5
8	1999, 20/20:04	M5	N27, E90	1999, 21.0–27.0	64 ± 13	16 ± 3
9	...[e]	...	...	1999, 114.5–116.7	<30	<7.4
10	1999, 123/06:02	M4/2N	N14, E32	1999, 124.0–128.5	22 ± 7	5.4 ± 1.7
11	1999, 152/~19:30	CME[f]	West limb	1999, 153.0–154.0	550 ± 110	135 ± 28
12	1999, 155/07:03	M3/2B	N17, W69	1999, 155.5–158.0	27 ± 6	6.6 ± 1.5

[a] From NOAA/Space Environment Center.
[b] Eruptive prominence on limb.
[c] Time period cut short due to instrument test.
[d] 1998 day 238 shock event excluded.
[e] No associated flare identified.
[f] Coronal mass ejection observed.

cycle. While this ^{3}He may be mixed in with other material with composition close to the corona, its presence at the 1% level is an indication that impulsive solar particle event material is present; in addition to ^{3}He, this impulsive SEP material would presumably include heavy ions with high ionization states such as those observed at higher energies in impulsive SEP events.

3. DISCUSSION

The average ^{3}He/^{4}He ratio in the 12 large SEP events surveyed here is a factor of ~5 greater than the typical slow solar wind (Gloeckler et al. 1999). This enrichment is similar to abundance variations observed in SEP events for ratios such as Fe/O (Reames 1995) and so might seem to fall within the range observed from event to event for other species. Indeed,
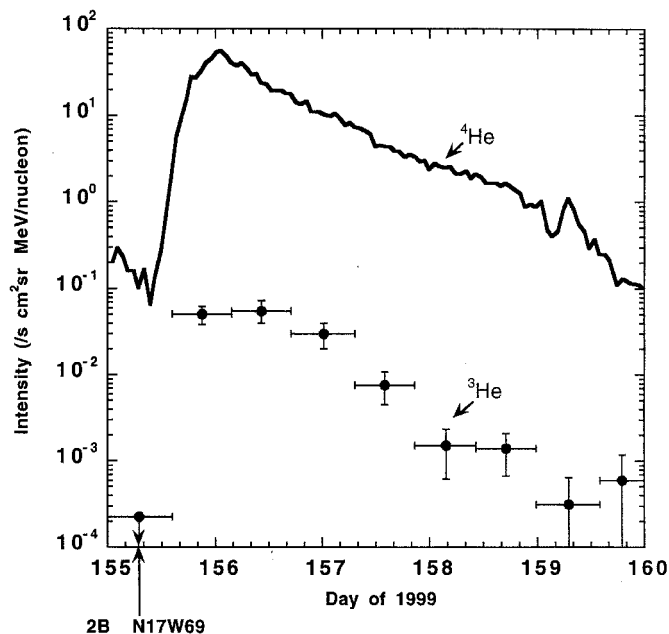
during our survey for the energy range 0.4–0.6 MeV nucleon^{-1}, Fe/O = 0.79 in the finite events and 0.19 in the upper limit events. However, in models for large solar particle events, enhancements in Fe/O are generally ascribed to the low first ionization potential (FIP) of Fe and/or the relatively low charge-to-mass ratio of Fe compared to O (Breneman & Stone 1985). For ^{3}He neither property applies since its FIP is higher, not lower, than that of O and its charge-to-mass ratio is higher, not lower, than that of O.

Given the common presence of ~0.2–2.0 MeV nucleon^{-1} ^{3}He in the interplanetary medium at 1 AU that we report here, we suggest that residual ^{3}He from impulsive SEP events forms a source material for ^{3}He seen in those large SEP events in which the ^{3}He intensity follows the time-intensity profile of other species. In those cases, the ^{3}He is accelerated out of this interplanetary suprathermal population by the same process that energizes other particles at these energies, namely the interplanetary shock. With an impulsive material "filling factor" of greater than 55% during our survey period, we might expect that large-scale shocks associated with large SEP events would often, *but not always,* pass through regions with remnant impulsive SEP material and energize it; this is consistent with the

FIG. 2.—The 0.7 MeV nucleon^{-1} ^{3}He and ^{4}He intensities for the 1999 day 155 large solar particle event. ^{4}He intensities are 1 hr averages; ^{3}He intensities are 12 hr averages.
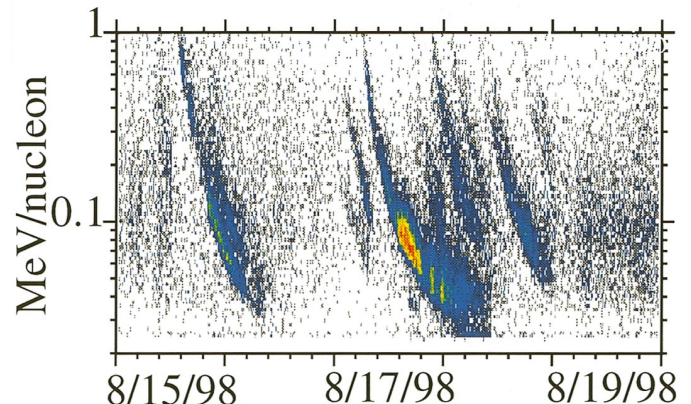

FIG. 3.—Spectrogram of low-energy ion intensities for a series of impulsive SEP events. A likely source of these events was Active Region 8299, which was located in the western hemisphere and produced numerous subflares.

Level	Characteristic Activity	Fe Intensity Range[a]	Number of Days	Fraction of Period
A	Very quiet	$0.001 < I$	184	0.34
B	Quiet	$0.001 < I < 0.01$	173	0.32
C	Impulsive SEP event	$0.01 < I < 0.1$	130	0.24
D	Large SEP event	$0.1 < I < 1.0$	35	0.07
E	Peak of large SEP event	$1.0 < I$	15	0.03

[a] In units of particles (s cm² sr MeV nucleon⁻¹)⁻¹.

Table 1 abundances where most but not all events have finite ³He. Because the impulsive SEP particle population is well into the suprathermal region, it could be expected to be efficiently accelerated since its energy greatly exceeds injection thresholds typically associated with interplanetary shocks. This same process could also in principle be responsible for the high-energy ³He/⁴He enhancements occasionally reported in large shock-associated SEP events cited above.

We note that recent solar particle ionization state measurements in large SEP events have found a transition from solar wind–like ionization states at low energies to high ionization states typical of impulsive events at higher energies (Oetliker et al. 1997; Mazur et al. 1999; Möbius et al. 1999b). Given the presence of impulsive SEP event ³He in the interplanetary medium reported here, heavy ions with impulsive characteristics would be expected to be present also. Direct ionization state measurements have been reported for three of the events in Table 1 that had enhanced ³He/⁴He ratios (events 2, 4, and 5); in all cases the energetic particle population included high charge state Fe, consistent with the presence of impulsive material (Mazur et al. 1999; Möbius et al. 1999a, 1999b). Of the four cases in Table 1 that had upper limits consistent with no enhancement of ³He/⁴He, ionization states have been reported in two cases (events 3 and 7), and both cases showed only low charge state Fe (Klecker et al. 1999; Möbius et al. 1999a), as expected if there were no impulsive SEP material present. SEP events with no impulsive material would arise when the interplanetary shock did *not* pass through impulsive SEP material. While the number of cases cited is admittedly small, we nevertheless believe it should be noted that in all cases in which a test can be made, the ³He/⁴He enrichments reported here coincide with the presence of high charge state Fe in the events and vice versa. Clearly it would be desirable to compare more cases of ³He enrichments along with Fe charge states. We also point out that surveying the ionization state of the quiet period Fe could also shed light on whether these high charge states are commonly present in the interplanetary medium, as is the case for ³He.
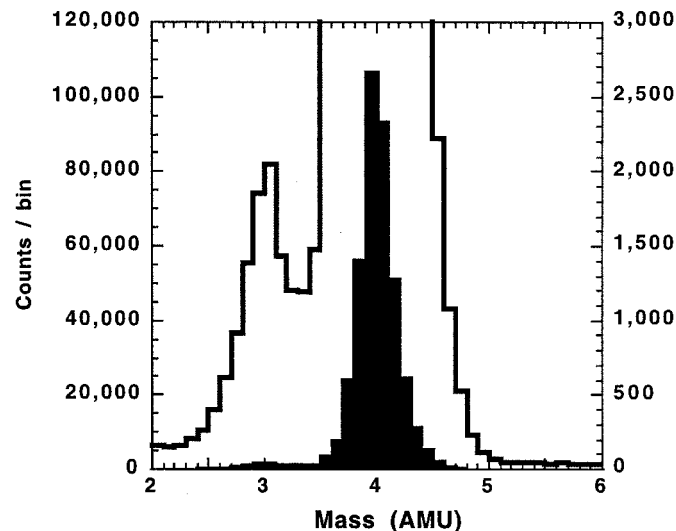

Fig. 4.—The 0.2–2.0 MeV nucleon⁻¹ mass histogram corresponding to intensity level B in Table 2; the left-hand scale applies to the shaded peak, and the right-hand scale is expanded to show the ³He region and background.

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